

How Vertical Wind Shear Affects Tropical Cyclone Intensity Change: An Overview

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1. Introduction

Over the last 30 years tropical cyclone (TC) intensity forecasts, for various (yet somewhat puzzling) reasons, have not achieved near the level of improvement of the TC track forecast. Although TCs have been studied intensively throughout the twentieth century, the community has surprisingly little quantitative knowledge as to how these storms interact with their environments, particularly with respect to changes in core structure (Frank & Ritchie, 1999). Rogers et al. (2006) stated that the lack of skill in numerical forecast of TC intensity can be partly attributed to inadequate understanding of the physics of TCs and the way they interact with their environment. In fact, TC structure and intensity changes are affected by a large and complex array of physical processes that govern the inner core structure and the interaction between the storm and both the underlying ocean and its atmospheric environment (Wang & Wu, 2004). Among other issues cited, crude parameterizations, difficulties in treating multiscale interactions, and the uncertainties involved with initializing the model over areas with sparse data coverage have received substantial attention.

In order to predict TC intensity, one of the important questions has been how to first accurately predict a TC's maximum potential intensity (MPI). Despite the fact that various methods for predicting a storm's MPI have been put forth, the failure of the NWP community to realistically forecast TC intensity largely lies in the fact that there are various unexplained processes keeping TCs from reaching their theoretical MPI. While the mechanisms involved are myriad, there are essentially two kinds that have been identified as having the largest impact on TC intensification: 1) internal dynamics and 2) external forcing from environmental flow. Below these two headings fall most TC intensity-related topics: vertical wind shear-induced asymmetries in the core region, the cooling of the sea surface due to oceanic upwelling under the eyewall region, the role of inner and outer rainbands, vortex Rossby waves (VRWs), embedded mesovortices, and eyewall cycles. Tropical cyclones often fail to reach their theoretical MPI because prominent MPI calculations use the basic assumption of TC axisymmetry (Camp & Montgomery, 2001), whereas TC structure is rarely symmetric, even in mature storms. While the tangential wind field and other TC features are axisymmetric, many significant features, such as VRWs, eyewall cycles, rainfall, convection, radial winds, and outer rainbands are often highly asymmetric attributes that impact TC intensity change; it is thus no surprise that nearly all TCs fail to reach their MPI.

The effect of storm asymmetries on TC intensification has been the subject of much debate, and it appears that the relationship is quite fundamental to the TC intensity change question overall. Of the many asymmetry-related topics affecting TC intensity, that of environmental vertical wind shear is one of the most prominently disputed in the TC intensity literature, perhaps partially because of its obvious relationship to storm asymmetry. This, however, is certainly not the only reason, as the basic physical mechanisms behind shear's effect on TC intensification are still not clear. Due to the prominence of the shear-intensification relationship and the questions that still remain, but despite the many other issues related to the TC asymmetry-intensification question, this is the field that we will be discussing for the duration of the chapter. First, early work discussing shear's effect on TC intensity will be overviewed. Following this will be a description of two of the most prominent theories that have been put forth: first, the mid-level warming hypothesis of DeMaria (1996) and then the venting hypothesis of Gray (1968) and Frank and Ritchie (2001). Afterwards a view of recent research will be given and, finally, some conclusions will be made.

2. Early work

While the effects of moderate vertical wind shear on TC intensification are now generally acknowledged to be quite nuanced, the early literature focuses more on their general effect on TC intensification without much debate as to the nature of the relationship; the seeds of the current discussions, however, were sown quite early. Despite the lack of proper atmospheric observations over much of the oceans, by the 1950s the scientific community had reached some general conclusions about TC formation. Besides the need for SSTs above 26°C and latitude greater than 5 to 8°, it was determined that high levels of vertical wind shear are prohibitive to TC intensification (Ramage, 1959). In his paper on the frequency of TCs in the various tropical basins, Ramage went on to describe the dearth of TCs over the China Sea, Bay of Bengal, and the Arabian Sea as being due to vertical shear associated with summer monsoon circulations.

Into the 1960s there was still little consensus as to the general environmental flow features and dynamical processes associated with TC formation (Gray, 1968). Using oceanic upper air data that had just recently become available, Gray published a seminal paper (Gray, 1968) that not only gave a substantive discussion on the atmospheric conditions that accompany TC formation, but also marked the beginning of the "venting" hypothesis (of core moisture and energy out of the top of the TC core) in explaining the method by which vertical shear inhibits TC growth.

Global in its reach, the study looked at over 300 TC development cases, analyzed the prevailing environmental characteristics of the recognized TC basins, and consistently found a strong association between regions of minima in climatological vertical shear and regions of frequent storm formation. Constricting the data by month, Gray found that this relationship held quite well temporally as well as spatially. In explaining these results he said that large levels of vertical shear produce a sizable ventilation of heat away from the developing disturbance. Thinking in terms of the TC core, the condensational heat released by convection in the upper troposphere is advected in a different direction relative to the center at lower levels. This asymmetry, he noted, was deadly for TC growth in that it renders the concentration of heat through the entire troposphere quite difficult (Gray, 1968). In stark contradiction to the findings of Gray (1968) and the community in general, Tuleya and Kurihara (1981) found that small (nonzero) levels of vertical shear, or moderate easterly

shear, were beneficial to TC development. They performed their study using an 11-level primitive equation model in which simple environmental flows were superposed on a shallow perturbation resembling an easterly wave. They explained these results by saying that both the formation of a relatively warm area in the upper levels, and significant moisture convergence in the lower levels, were necessary for TC growth. If these two events were strongly coupled in the vertical then an intensification feedback between the two could occur. They found that surface easterlies were beneficial (along with the easterly shear) for TC development because they promoted a strong coupling between the upper and lower levels. While subsequent studies did not make much mention of the benefits of easterly shear on TC, this early study was notable in that it emphasized the importance of the coupling of the upper and lower levels on the mechanics of intensity change. Later this same topic would command the attention of many as they strove to explain the processes behind the way in which TCs often maintained this coupling despite the influence of vertical shear.

With the increasing interest in TC maximum potential intensity, Merrill (1988) set out to determine the role of shear in keeping a TC from reaching this theoretical upper limit. To do so he used composite National Hurricane Center (NHC) upper-tropospheric observational data from rawinsondes, satellites, and commercial aircraft to study how TC environments differ for developing and nondeveloping storms. His study included 28 hurricanes from the Atlantic basin which were segregated depending on 1) intensity change over a 24 hour period, 2) the proximity of the storm to its maximum potential intensity (or efficiency), and 3) the corresponding climatological SSTs in the storm's vicinity. Considering vertical shear as being the main component of what kept certain storms well below their MPI, Merrill analyzed the data from such storms and concluded, as expected, that vertical shear is lower for intensifying hurricanes; interestingly, he found this to be especially the case at radii of 1000 km or more.

Having sufficiently established the detrimental effect of shear on TC intensification, subsequent studies moved into the mechanisms that lay behind the interaction. These studies took numerous forms and included such topics as the effect of shear on TC movement (Shapiro, 1992; Flatau et al., 1994; Wang & Holland, 1996), the effect of shear on the distribution of convection (Corbosiero & Molinari, 2002; Rodgers et al., 2003; Chen et al., 2006), the way in which TCs with certain characteristics (i.e., a certain strength, horizontal extent, or latitude) are able to better resist shear and how the TC can maintain its vortex nearly vertical in areas of adverse environmental conditions (Jones, 1995; DeMaria, 1996).

Due to disparate research findings, many researchers in the 1990s investigated the way in which vertical shear influences the movement of the storm relative to what the usual environmental steering flow would dictate. Flatau et al. (1994) adeptly began by basing his study on the observation, by Gryanik and Tevs (1989), that, when considering the displacement of the centers of a low-level cyclone and upper-level anticyclone relative to one other, the lower- and upper-level vortices can be thought of as interacting in a manner similar to the interaction of two-dimensional vortices on a horizontal plane.

Using his semispectral, primitive equation model to simulate the movement of a baroclinic vortex, Flatau et al. (1994) found that in westerly linear shear the simulated TC vortex moved toward the north, while in easterly shear the vortex propagated southward. These results contrasted with those of Shapiro (1992), who, when performing similar tests using a three-layer multinested model with a compressible fluid, found southward propagation in

westerly sheared environmental flow. Flatau et al. (1994) attributed these differences to 1) the fact that the direction of propagation depends on the position of the upper and lower PV anomalies relative to each other; 2) differences in the two papers' respective wind profiles; and 3) the effects of the background potential vorticity gradient. While these details may seem irrelevant to a discussion on TC intensification, the reasons why Flatau et al. and Shapiro drew their particular conclusions presaged the way in which later researchers explained the methods used by TCs to cope with vertical shears and a tilting vortex. First, Flatau et al.'s motion explanation depends upon the relative movement and interaction between the upper and lower levels of the vortex. In westerly vertical shear the upper-level anticyclone is pushed east of the lower-level anticyclone. The cyclone-anticyclone pair moves toward the north due to the fact that the low-level PV anomaly (by which the TC center is often described) advects the upper-level negative PV anomaly and vice versa.

Despite the contradicting results, Shapiro (1992) and Flatau et al.'s (1994) work both involved TC propagation as caused by a similar interaction between TC layers and the same horizontal transport of potential vorticity. Using a 5-layer primitive equation model on both an f -plane and β -plane, Wang and Holland (1996) also found that under most circumstances the surface vortex was advected to the left of the vertical shear. They too noted that the leftward or rightward enhancement of propagation relative to the vertical shear depended on the relative magnitude of the different motion tendencies. The fact that all three of these motion studies (Shapiro, 1992; Flatau et al., 1994; Wang & Holland, 1996) relied all or partially on the interaction of the upper and lower PV anomalies as a means to explain TC movement lent credence to the importance of vortex tilt and the myriad consequences and complications that arose from this phenomena. The interesting part of the Wang and Holland (1996) paper is the fact that they started to attribute a significant amount of the tilt-reducing coupling (especially for strong and large vortices) to the relative positioning of the upper and lower-level cyclone, not the lower-level cyclone and the upper-level anticyclone, as had the majority of the previous studies had done when looking to explain the way in which shear affected TC structure.

Much of the present day discussion revolves around the behavior and characteristics of the tilt of the cyclonic portion of the TC core. As vertical shear results in the differential advection of PV, this tilt can become quite pronounced and is often used as a proxy for the overall impact vertical shear has on the TC core. The tilt is often an effective way to analyze the shear-intensity relationship not only because of its central role in TC core dynamics, but also because of its ubiquity. For example, Huntley and Diercks (1981), looking at difference between the TC core at the 500 and 700hPa levels, noted that there was evidence of tilt in excess of 100km in 11 of 23 named TCs during the 1979 West Pacific Typhoon season. In addition, they noted that the tilt extended to much higher levels, and, foreshadowing much of the research that was to come, said that the tilt was highly correlated with the magnitude and direction of the vertical shear.

Despite the similarities with other prominent studies of their day, Flatau et al. (1994) in particular pointed the way forward in terms of vortex layer coupling by demonstrating that the vortex tilt is somewhat mitigated by the presence of diabatic heating by upward advection of high PV air at the center and downward advection of low PV at larger radius. Along with Wang and Li (1992), Flatau et al. (1994) considers this the primary means by which a vortex remains vertically coupled, although they do not discuss exactly how the vertical circulation contributes to this coupling (Jones, 1995). This coupling is central to the explanation of how shear affects TC intensification, as it seems to be one of the primary

ways in which vertical shear (and environmental influences in general) interacts with TC structure. Explaining and determining the abilities of these vertical coupling mechanisms for the various sizes, intensities, and positions of TCs essentially determines their abilities to resist vertical shear and it thus provides us good reason for including the seemingly tangentially related discussion on TC movement.

This background enables us to discuss the way in which this internal coupling takes place and how exactly it relates to the way in which sustained levels of shear negatively impact TC intensification. While the PV and θ_e “venting” theories regarding the shear-intensification relationship are not too elaborate, the important midlevel warming theory does require a bit of backdrop.

3. The Midlevel warming hypothesis

As mentioned, Wang and Holland (1996) alluded to the importance of looking at just the tilt of the cyclonic vortex itself, without explicitly considering the impact of the positioning of the upper-level anticyclone and lower-level cyclone. Towards the mid-1990s this new way of analyzing the impact of shear on TC intensity was becoming quite ubiquitous. The literature was now focusing more on the coping mechanisms used solely by the TCs’ cyclone (now ignoring the anticyclone) to withstand vertical shear and why these coping mechanisms often broke down for certain TC characteristics; the impact of this shear was now inexorably associated with the tilt of the cyclonic vortex and the interactions between its upper and lower levels.

This refined way of thinking of the shear-intensity relationship was perhaps most importantly spelled out in a landmark paper by Jones (1995). Despite the extensive amount of relevant research done in this field at the time, her paper stands out as a standard which laid much of the groundwork behind the midlevel warming hypothesis. Jones’ (1995) paper is based on her research done by looking at the behavior of initially-barotropic vortices in environmental flows. Her calculations were performed using a dry, hydrostatic primitive-equation numerical model on an f-plane. Despite the fact that she was performing barotropic simulations of TC vortices and examining the dynamical and adiabatic mechanisms that countered vertical shear, her explanations of such were so fundamental to the shear-intensity relationship that even later diabatic descriptions, such as the midlevel warming theory, owe much to her research.

Broadly, Jones’ work was closely aligned with that of Flatau et al. (and other contemporaries), in that she was using a three-dimensional primitive equation model whose results indicate that the vertical shear of the environmental flow results in differential advection of the storm’s potential vorticity. Her approach was unique for her time, however, in that, in order to isolate the vertical coupling mechanism between vortex levels, she performed her studies without the inclusion of diabatic processes, as she believed that none of the TC shear coping mechanisms depended on the presence of these processes inherent in tropical cyclones. Jones specified the shear such that there was no potential vorticity gradient; the resulting absence of diabatic effects precluded the development of an upper-level anticyclone. Partly due to this technique, future researchers looked almost exclusively to the cyclonic tilt to explain the shear-intensity relationship without dwelling on the complicating implications of the anticyclone.

Jones’ (1995) interest in the vertical coupling mechanisms was piqued when, in specifying a westerly flow where a 4m/s wind at the surface decreased to 0 at the model top (at 10km),

she found that the vertical tilt of the accompanying vortex was much smaller than that which would be implied by simple advection by the basic flow. As imagined, the lower-level vortex was first displaced to the east of the upper-level vortex. Upon investigating, she found that the subsequent motion of the surface center has a northward component, while the motion of the upper-level center has a southward component. This resulted in the fact that, while the center at 5km height was moving almost due east, the upper- and lower-level centers revolved cyclonically about it. After 24 hours this resulted in the fact that the vortex at lower levels is located to the west of the vortex at upper levels, which tilt is opposite to that which would be expected from the direction of the vertical shear.

This response of the TC to vertical shear can be explained by first thinking of the initial flow as consisting of two identical potential-vorticity anomalies, which consist of an upper and a lower anomaly that initially line up in the vertical and are under the wind regime specified above. As the lower level anomaly is displaced to the east, because of the shear, the upper level anomaly remains in its prior position. The downward projection of the upper anomaly gives a cyclonic circulation at the surface; since the lower anomaly is displaced to the east, it thus has a southerly component across its center because of the effect of the upper anomaly. This tends to advect the lower anomaly to the north until the line joining the centers of the two anomalies no longer lies in the east-west direction; this leads the downward projection to create an easterly component of the wind onto the lower level anomaly. Thus both the upper and lower anomalies continue to revolve around each other in a cyclonic manner.

Once this cyclonic revolution results in the upper- and lower-level anomalies being aligned in the north-south direction, the downward projection of the upper-level anomaly has a purely easterly component across the lower anomaly; thus, considering that the shear was specified as having a lower-level westerly flow, this particular vertical orientation of the PV anomalies acts as a significant coping mechanism enjoyed by the TC to counter the effects of vertical wind shear. A second, related, coping mechanism is that which comes about after the mutual anomaly revolution has placed the lower-level anomaly west of the upper-level anomaly. With the tilt now leaning into the wind, the environmental shear, in this case, works to reduce the vortex tilt and thus promotes a stable TC structure. Of course, these effects can be, and are, reversed. When the lower-level anomaly is south of the upper, the downward projection ceases to counter the shear and thus ceases to promote vortex alignment; similarly, when the lower-level anomaly is east of the upper, the vertical shear is exacerbating the vertical vortex tilt.

More directly relevant to the central theme of this paper is Jones' (1995) discussion of the vertical circulations that result from the impact of sheared environmental flows. In basic terms, the development of the vertical circulation can be associated with the maintenance of equilibrium. Once the vertical circulation tilts the PV anomaly, a thermal adjustment is required for the flow to be balanced; this is composed of a cooling down-shear and a warming up-shear. This cooling down-shear raises the isentropes there and later leads to adiabatic vertical motion, as parcels moving tangentially around the TC center follow the isentropes upward as they pass the down-shear part of the storm.

Since there are no diabatic processes in her model that could produce thermal anomalies, Jones (1995) concludes that these departures from the initial potential-temperature field can arise only due to the advection of the environmental temperature field by the vortex flow. After analyzing her barotropic cyclone simulations she noted that, after the cyclonically-rotating-upper-and-lower-PV-anomaly mechanism, these vertical motions are the second major way she believed a TC maintained an upright vortex in significant levels of shear. As

the strength of the temperature anomalies required to maintain thermal wind balance depends on the size of the vertical tilt, the strength of the vertical velocity will also depend upon the size of the tilt. When modeling the behavior of a vortex, these are very measurable parameters that, at least adiabatically, have a seemingly clear relationship. Analyzing the durability of this relationship would enable the researcher to determine how general TC characteristics alter the storms' ability to withstand vertical shear.

While Jones (1995) discussed the TC adiabatic response, Flatau et al. (1994) had examined the importance of the diabatic secondary circulation to the ability of a TC to resist shear. He explained that this was manifested in the transport of high PV air from below at the center and downward advection of low PV air at larger radius; however, Jones (1995) noted that this did not sufficiently explain how the diabatic effects contributed to vortex coupling.

Both diabatic and adiabatic components of the TC vertical circulation's response to vertical shear play a central role in its relationship with TC intensity change. How this was so was explained in an important paper by DeMaria (1996), who is the principal author of the midlevel warming hypothesis with regard to the way in which vertical shear impacts TC intensity. In essence, his theory comes from an analysis of the consequences of the shear-induced PV tilt. As stated, the vortex tilt is accompanied by a change in thermal structure of the vortex so that the mass and wind fields remain quasi-balanced. His hypothesis is that these tilt related variations in the thermal structure affect atmospheric stability near the storm center, and thus storm intensity.

Essentially, the horizontal displacement of upper and lower PV anomalies causes a thermal shift such that there are colder relative temperatures down-tilt, and warmer temperatures in the direction of the low-level PV anomaly (or up-tilt). While this had been noticed previously (Jones, 1995), DeMaria (1996) made the astute observation that the midlevel temperature increases near the low-level vortex center. He also made the observation that the relative temperature changes associated with the vortex tilt will not only lead to a decrease in convection near the low-level center (because of the warming), but it will also lead to increased convection outside the eyewall which would further disrupt storm symmetry and circulation.

In order to test his hypothesis, DeMaria (1996) used a simple, two-layer barotropic model, as this was determined to be the simplest context in which the effects of vertical shear could be illustrated. For prognostic equations, he used the two horizontal momentum equations and the continuity equation for height. He also employed a PV approach to the model flow analysis. This is often an effective approach for a two-layer model, as the entire flow field can be determined from the PV distribution with suitable boundary conditions and a balance between the mass and wind fields.

The barotropic approach, which, by definition, neglects the upper level anticyclone, can be quite accurate in simulating intense storms, as such TCs often have cyclonic circulations that extend through the depth of the troposphere. Because of this fact, and then-recently published research, DeMaria (1996) decided to focus exclusively on the positive PV anomaly in both model layers. He made this decision partially based on the fact that Shapiro and Franklin (1995), in studying Hurricane Gloria, indicated that there was a core of high PV values within 150km radius of the storm center that extended up to at least 200hPa. The fact that this important study from DeMaria (1996) and that that from Jones (1995) both produced their vortex simulations using a at least initially, barotropic vortex, and thus essentially ignored the upper-level anticyclone, demonstrates the way in which the community had changed its way of thinking about TC tilt. Considering that only a decade

earlier the widely accepted method of viewing the TC response to storm tilt was related to the interaction between the upper-level anticyclone and lower-level cyclone, this represents a notable sea change in the analysis of the TC shear-intensity relationship.

In order to simulate the effects of TC tilt on midlevel warming, DeMaria (1996) performed several experiments in which he placed the low-level PV anomaly at the domain center with the upper-level anomaly displaced to the east. After using upper-level eastward displacements of 0, 20, 40, and 60km, he observed that the midlevel temperature consistently increased near the low-level vortex center in order to maintain balance. He found that the maximum midlevel temperature anomaly had increased by roughly 3K when the upper-level PV anomaly was displaced 60km (at radius of maximum wind) to the east of the low-level vortex center. This level of midlevel warming, if experienced in a real TC, would be sufficient to inhibit convection and thus weaken TC intensity. Essentially, at 60km of horizontal displacement, the meridional component of the winds from each level have their maxima in terms of positioning vis-à-vis the center of the opposite layer. DeMaria (1996) hypothesized that not only would the tilt-induced midlevel warming prove inhibitive of convection and TC intensification, but the increase in asymmetry due to the increased convection down-tilt of the storm's low-level axis of rotation also appeared to hinder coherent storm structure and intensification.

As mentioned, for a purely eastward displacement, the overlapping winds at the centers of the PV anomalies would be increasingly meridional; in DeMaria's (1996) work, this maximum meridional wind (and maximum PV anomaly interaction) occurs at a displacement of 60km. DeMaria (1996) echoes Jones (1995) in explaining that the resulting cyclonic revolution of upper- and lower-level PV anomalies works to resist the effects of vertical wind shear. He then goes on to perform a regression analysis for all named TCs from the Atlantic basin to determine the relationship between shear and intensification for various types of TCs, the reasons for which will be discussed below.

While examining the mechanism by which a TC weakens in vertical shear is the topic of interest in this chapter, it is also of interest to know why these processes occasionally break down, as seen in TCs which appear to be able to strengthen in adverse environments. This interest has mainly been manifested by those in the DeMaria camp, because of the effect of various environmental parameters on the extent of TC vertical coupling, and thus it will now be discussed as an extension of the midlevel warming hypothesis.

The resistance of a vortex to vertical shear is a function of the Rossby penetration depth (D), which is a measure of the amount of vertical coupling in a TC. This parameter can explain the way in which many different factors can affect the tilt and rotation rate of a vortex. A few of these major influences include the Coriolis parameter, the strength of the vortex, static stability, the height of the vortex, and the width of the vortex. Accordingly, DeMaria (1996), in his TC regression analysis, used TC latitude, intensity, and size when analyzing the predictability of the shear-intensity relationship. He posited that TCs were more able to mitigate shear's impact when they were strong, large, and at higher latitudes.

Just the year before, Jones (1995) performed several penetration depth-related tests using her dry, primitive equation model on an f -plane while simulating initially barotropic vortices. Specifically, she used her model to look at how the magnitude of the vertical penetration depth depended on the Coriolis parameter, vortex strength, static stability, and horizontal length scale. She found that a weaker vortex (with a max tangential wind of 20m/s instead of 30m/s) led to a slower upper- and lower-level relative revolution rate and greater vertical tilt. Worth noting, however, is her explanation for why this took place; despite it making

intuitive sense, she renders the mechanisms involved especially lucidly. Seeing that, in a weaker vortex, the tangential flow at the level of the upper-level PV anomaly is reduced, the flow due to the downward projection is also weaker. This results in reduced advection at a given level due to anomalies at other levels (Jones, 1995). The weaker vortex cannot counter the shear because its upper-level and lower-level PV anomalies cannot revolve (cyclonically) sufficiently for the resulting tilt to counter the prevailing shear.

When similarly conducting experiments by changing the Coriolis parameter she found that by increasing the latitude, from 12.5° N to 20° N, at which the f-plane is situated, the vortex manifested significantly less tilt, with a greater revolution rate. This was attributed to the fact that, everything else being equal, a higher Coriolis parameter would cause the isentropes to be more strongly tilted; since the TC's method to counter shear depends on the dynamic and thermodynamic processes having to adjust to these tilted isentropes, this increased revolution rate is expected. Jones (1995) also performed analogous experiments related to the length scale and height of the vortex and found that an increasing TC width led to a smaller vertical tilt and a greater revolution rate, whereas a higher vortex top led to a larger vortex tilt and smaller revolution rate, as the vertical coupling would obviously be reduced as vertical scale increases.

While Jones' (1995) simulations and DeMaria's (1996) six-year case study confirmed what had been hypothesized about the effects of penetration depth, their work did go a step further in that they quantified these effects through their model runs, multiyear analyses, and development of penetration depth equations. Jones (1995) first attempted to use quasi-geostrophic theory to define penetration depth, where f is the Coriolis parameter, L is the length scale, and N is the static stability. Using typical scales for her particular model, she came up with a depth of 930m. Admitting that that was unreasonable, largely because of the fact that TCs experience significant ageostrophic vertical motions, she then turned to the work of Hoskins et al. (1985) and Shapiro and Montgomery (1993), who formulated an alternate expression for penetration depth of an axisymmetric vortex as being

$$(f_{loc}(f + \zeta))^{1/2} L / N, \text{ where } f_{loc} = f + 2v_T / r \quad (1)$$

and ζ is the vertical component of vorticity. Noting the fact that the vorticity profile of her vortex was strongly peaked, she expressed concern as to how to use the above formula, but ultimately used average values of relative vorticity and tangential winds and found a reasonable Rossby penetration depth of 14km. Nevertheless, she still was not satisfied with these methods and conceded that, for the parameters involved in her experiments, it was not entirely clear how a penetration depth should be defined. DeMaria (1996) made attempts similar to those of Jones (1995) in an effort to define penetration depth for his particular model setup and appears to have enjoyed more success. To begin, he referenced the work of Shapiro and Montgomery (1993) as he looked to define Rossby penetration depth for the general atmosphere; this is done by solving the definition of the local Rossby radius for an axisymmetric vortex for the vertical scale, which gives

$$D \sim \frac{IL_R}{N}, \quad (2)$$

where L_R is the horizontal scale, N is the static stability and I is the inertial stability parameter defined by

$$I = \left[(f + \zeta) \left(f + \frac{2V}{r} \right) \right]^{1/2} \quad (3)$$

where V is the tangential wind and r is the radius. Equations 2 and 3 plainly show that D increases with latitude, length scale, and intensity (V and ζ) and decreases with static stability; DeMaria (1996) then went on to define D for his two-layer model using quasi-geostrophic arguments, which, while clever, are not relevant here. Equations 2 and 3 will suffice in giving an idea of what type of resistance to vertical shear a particular tropical cyclone will exhibit.

4. The venting hypothesis

While the inner-core θ_e venting hypothesis of Gray (1968) is somewhat simple, its effect, nonetheless, is not very well understood, as some would see the cooling in the upper-levels (upon which the theory is based) as a destabilizing factor beneficial to TC development (DeMaria, 1996). While both modeling (Frank & Ritchie, 2001) and observational studies (Knaff et al., 2004) have convincingly shown that TCs weaken from the top down through a vertical lowering of the upper-level warm core and accompanying vortex, it is also still not clear how this core erosion occurs. Thus, a bit of background regarding the theory and its beginnings, development, and treatment will be beneficial in order to understand the current state of research.

Gray (1968), in his global observational study of atmospheric conditions surrounding TC development, is noted as being the first to elucidate the venting hypothesis as a method by which to explain the effect of shear on TC intensity. He concluded that the dynamics of TC development are best viewed as a hydrostatic problem of temperature-pressure-wind adjustment. In his opinion, to form and maintain a TC, the mean tropospheric temperature must be increased and concentrated. This is a typical view of those in the venting camp; the strength of a TC is seen as being concentrated and maintained in the upper levels of the core, primarily manifested in high levels of equivalent potential temperature and potential vorticity. Gray (1968) explained shear's impact as producing a large ventilation of heat away from the developing disturbance. He found that the condensational heat released by the cumulus convection to the upper troposphere was advected in a different direction relative to the heat released at lower levels. The loss of heat in the core would lead to a hydrostatic adjustment to a higher minimum pressure and thus a weaker TC.

Through the following decades, there was little talk in the literature about the venting hypothesis as most TC researchers were more concerned with shear's effects on TC track (Shapiro, 1992; Flatau et al., 1994; Wang & Holland, 1996), TC structure (Bender, 1997), and with specifying the effect of different types of shear on TC intensity (Tuleya & Kurihara, 1981; Merrill, 1998), rather than how exactly shear produced these effects. However, as mentioned, general explanations as to how these processes occurred generally focused on dynamical processes (Jones, 1995), midlevel warming (DeMaria, 1996), and asymmetries between surface fluxes and moisture convergence (Peng et al., 1999).

Around the year 2000, there was renewed interest in the venting hypothesis because of the interesting results produced by Frank and Ritchie (1999 & 2001). In their discussions regarding this method of explaining TCs' reaction to shear, the arguments center on a few general tenets. First is the fact that the flux of θ_e and PV out of the core is responsible for TC

weakening; the second is the positioning of the PV and θ_e maxima relative to the core; and the third is based on the fact that the TCs are seen as weakening from the top down, which ties in closely with the first two.

In their 2001 paper, using the MM5 with three embedded meshes, a 5km grid spacing, and a fully explicit representation of the moist convective processes, they examined the response of mature, idealized hurricane-like vortices to various types and magnitudes of vertical wind shear. The MM5 solves the nonlinear, primitive equations using Cartesian coordinates in the horizontal and a terrain-following sigma coordinate in the vertical. This new type of model was crucial to the goals of their study as numerical simulations of tropical cyclone-shear interactions require a model with a very large domain that is capable of resolving the storm's environment and external circulation features, as well as a high-resolution core region capable of resolving the small, intense core processes of the storm (Frank & Ritchie, 1999). Their simulations were performed on an f-plane centered on 15 degrees north, so that complications would not arise from the interaction between the storm flow and the planetary meridional absolute vorticity gradient, as these can often alter the mean flow in the storm's core region (Frank & Ritchie, 2001).

Looking at wind regimes of 1) no large-scale flow, 2) easterly flow, 3) 5m/s shear, 4) 10m/s shear, and 5) 15m/s shear (whose sheared winds varied from the surface to the upper-troposphere), they found that, in the case of a vortex in shear, as opposed to a vortex embedded in uniform zonal flow, the weakening of the storms took place through a well defined, multistep process. First, the storm core develops a strong, wavenumber one asymmetry with regard to vertical motion, rainfall, and cloud water at most levels, shortly after the shear is applied. The asymmetry is then great enough so that upper-levels of θ_e and PV lose their concentration in the eye of the storm and become concentrated solely within portions of the eyewall and other rainbands; this occurs primarily through outward eddy fluxes. This loss of core warmth leads to an increase in surface pressure, which decreases the circulation at all levels. This asymmetric pattern then moves down with time, accompanying the tilt's progression, such that the structure continues to weaken. At some point this is halted because the stronger circulation at lower levels somewhat preserves the symmetric vortex, such that equilibrium is reached at an intensity well below the storm's MPI.

As to how well these storms were able to avoid this process and withstand shear, Frank and Ritchie (2001) report that the vortex in 5m/s shear was able to maintain its strong, vertically aligned structure for about a day and a half, while the vortex in 10m/s shear continues to strengthen for 18-24 hr before weakening. While shear of 15m/s tore an intense, idealized storm apart within about one day, the delayed response of the storm under light shear suggests that the processes that tend to keep the storm axisymmetric are able to temporarily overcome shear of less than 10m/s.

DeMaria subsequently worked with Knaff et al. (2004) to perform a composite analysis of TC warm cores as they relate to various levels of shear. What was unique about this study is that they used temperature soundings from the Advanced Microwave Sounding Unit (AMSU) A instruments to analyze the characteristics of 186 TCs in various levels of shear from 1999-2002 TC seasons in the Atlantic and east Pacific basins and from May-December 2002 for the western North Pacific. Defining shear as the 24 hr averaged vector difference of the horizontal wind between 200 and 850hPa, they created two TC composites. One was for intense storms (46-52m/s maximum surface winds) that displayed favorable shear conditions (<7.5m/s) and the other included intense storms that were experiencing significant shear (>7.5m/s); comparing the two composites, they analyzed the inner core

temperature anomalies in hopes of finding a consistent change in the TC axisymmetric thermal structure due to shear variations.

Knaff et al. (2004) calculated the TC temperature anomalies relative to the azimuthally and radially averaged temperature from a 500-600km radius and found that, as the shear increases, the height of the balanced hurricane vortex decreases. Confirming the results of Frank and Ritchie (2001), Knaff et al. (2004) concluded that the general effect of vertical shear on a mature TC is the top-down erosion of its warm-core structure due to the downward propagating horizontal fluxes of potential temperature, although they admitted they weren't sure how this occurred.

5. Recent developments

Much of the recent work in this field, besides directly addressing or confirming the results above (Jones 2000; Wong and Chan 2004), looks into which large-scale parameters accompany TC intensification (Paterson et al., 2005; Zeng et al., 2007,2008; Garner et al., 2009; Hendricks et al., 2009), discussed how TC asymmetries affect storm intensity (Yang et al., 2007; Sang et al. 2008), examines the role of turbulent fluxes on intensification (Zhu, 2008; Bryan and Rotunno, 2009; Rotunno, 2009), and proposes several new mechanisms and frameworks to describe the way TCs are detrimentally affected by shear (Reasor et al., 2004; Riemer et al., 2009; Tang and Emanuel 2010). Using a primitive equation model to study baroclinic vortices on an *f*-plane, Jones (2000) found, contrary to the work of DeMaria (1996), that shear-induced tilt in the TC core region may actually reduce stability in certain parts of the vortex, although the implications for TC intensity weren't entirely clear. Similar to the studies of Frank and Ritchie (1999,2001), Wang and Chan (2004) used the MM5 at 4km resolution to analyze the response of idealized TCs on an *f*-plane to various levels of vertical shear. What they found was that while TCs under shears of 6-8m/s are not as intense as TCs under no shear, it's only under shears above 10m/s when a TC weakens significantly. Confirming the results of Jones (1995), they found that TCs resist tilt by a mutual rotation between the various levels; they also found that there was significant warming in the lower half of the troposphere near the center of the TC, which may corroborate part of what DeMaria (1996) was seeing happen in the midlevels of his TCs.

In the last five years there have been several attempts to distinguish the environmental characteristics most favorable for TC intensification. Using NCEP-NCAR reanalyses, Paterson et al. (2005) found that, in the Australian region, shears of 2-4m/s actually favor significant intensification and shears above 12m/s favored rapid weakening; using the same data, Zeng et al. (2007) examined the effect of transitional speed and vertical shear on TC intensification in the North Pacific and North Atlantic (Zeng et al., 2008) from 1981-2003. They found that few TCs intensified when their environmental wind shear was above 20m/s and they developed a new empirical maximum potential intensity (MPI) which includes the combined negative effect of translational speed and vertical shear. Hendricks et al. (2009) similarly used the NOGAPS global analysis and the TRMM Microwave Imager (TMI) to examine environmental and climatological characteristics of tropical cyclones undergoing different intensity changes in the western North Pacific and North Atlantic basins. Interestingly, they found that the environment of rapidly intensifying TCs and moderately intensifying TCs is quite similar. The exceptions to this was the fact that in the Atlantic rapid intensification (RI) events occurred in environments with weaker deep-layer shear than moderately intensifying events; an important finding was that the rate of TC

intensification was not critically dependent on SSTs. Using a compressible, hydrostatic, dynamical model nested in global analysis fields to investigate the relative effects of shear and thermal stratification on TC variability, Garner et al. (2009) found that the sensitivity of the model's tropical storm activity to projected changes in vertical shear was substantial; projecting through the 21st century according to the IPCC's A1B scenario, it was found that the model's reduction in Atlantic tropical cyclone activity was largely driven by the increased seasonal-mean vertical shear in the western Atlantic and Caribbean (Garner et al., 2009). While all of this serves to confirm the importance of vertical shear in TC intensification, there have also been many recent, forward-looking papers helping to explain the nature of the relationship.

In the last ten years one of the most unique studies was that of Reasor et al. (2004), who, employing a Boussinesq PE model to simulate barotropic vortices on an f -plane, found that VRWs, rather than the diabatic secondary circulation, are primarily responsible for a TC's resistance to shear. Notably, this resistance was sustained for shears above 10m/s without the direct aid of cumulus convection. While their work explained several neglected topics (e.g., the presence of quasi-stationary tilted states for a TC in shear and the prominence of radially and azimuthally propagating VRWs that arise from a TC forced by shear), they admit that the much-debated role of diabatic processes on TC resiliency was still unclear. Subsequently, Riemer et al. (2009) developed a new explanation of the vertical shear-intensity relationship. He emphasized the role of downdrafts and their transport of low θ_e air from the mid-troposphere into the boundary layer and its effect on eyewall energetics from a Carnot perspective. Relatedly, Tang and Emanuel (2010) established an idealized framework based on steadiness, axisymmetry, and slantwise neutrality to assess how shear-related ventilation affects TC intensity via downdrafts outside the eyewall and through midlevel eddy fluxes directly into the eyewall. As did Riemer et al. (2009), Tang and Emanuel (2010) explain mechanisms' detrimental effect on TC intensity by considering the storm as a Carnot heat engine; when these shear-related processes reduce the maximum entropy present in the core of the TC, and thus decrease the thermodynamic efficiency, the result is a decrease in the total amount of work that can be performed by the TC in combating frictional dissipation. As mentioned by many previous papers, TCs with higher potential intensities (PIs) are better able to withstand wind shear as the steady state intensity increases while the minimum intensity needed for sustainability decreases with increasing potential intensity (Tang and Emanuel 2010). It thus is well established that vertical shear leads to a decrease in the amount of energy available to the TC to be used as work, however, exactly where and how this occurs is still being debated.

As mentioned in the research of Frank and Ritchie (2001), it appears that turbulent eddies play a key, yet little understood role in the shear-related venting that works to reduce a TC's thermodynamic efficiency. The importance of this turbulent flux on TC intensification has recently come to the fore due to 2 papers involving Richard Rotunno. First, in Bryan and Rotunno (2009), they touched on the subject indirectly when using an axisymmetric numerical model to evaluate the maximum PIs of tropical cyclones. They showed that turbulence in the radial direction limits maximum intensity by weakening the radial gradients of angular momentum and of entropy; maximum wind speed turned out to be very dependent on horizontal mixing length (Bryan and Rotunno, 2009). Echoing Frank and Ritchie (2001), they subsequently declared that the difficulty in real time forecasts of intensity may be partly related to the specification of turbulence in NWP models and/or the

general lack of understanding of turbulence effects in hurricanes (Bryan and Rotunno, 2009). Considering the typical mesoscale model has a resolution of 1-3km and much of the critical venting occurs through turbulent eddies on the order 100m the importance of the models' ability to resolve or approximate turbulence is essential.

Building on this fact, Rotunno et al. (2009) published a study which examined the importance of turbulent transfer on TC modeling using a large-eddy simulation of a tropical cyclone using the Advanced Research WRF. Employing six nested grids with a horizontal resolution of 62m, they analyzed the impact of the resolution of turbulent eddies on maximum TC wind speed. They found that the storm strength increased significantly when the grid spacing was reduced while the turbulence was parameterized (from 1.67km to 185m), but the mean winds actually decreased when increasing the resolution from 185 to 62m, as turbulent eddies are now being resolved (Rotunno et al., 2009). Especially interesting is the fact that the study confirmed that there is strong turbulence along the inner edge of the eyewall of intense hurricanes; considering the essential role turbulence plays in several hypothesis concerning venting in this part of the TC (Frank and Ritchie, 2001; Tang and Emanuel, 2010), this area of research is key to being able to explain how TCs interact with their environment. Further, the clear dependence of mean TC intensity and radius of the TC eyewall on the effects of resolved turbulence demonstrates the importance of correctly approximating turbulent diffusion when modeling TC intensification.

Recently, research conducted by Thatcher (2010) attempted to address whether a TC is negatively impacted by vertical shear through a midlevel warming (DeMaria, 1996) or an upper-level entropy venting (Frank & Ritchie, 2001). Using the WRF-ARW at a 3km grid spacing while simulating Typhoon Jangmi (2008), it was found that the TC's intensification ended while under moderate shear (~7m/s) due to the establishment of a theta-e maxima from 200-300hPa in the eyewall; prior to this, the concentration had been relatively uniform across the core of the TC at upper-levels. It was found that Jangmi's mean sea-level pressure (MSLP) was most sensitive to theta-e values from 200-300hPa in the inner part of the eyewall (30-50km). The end of the intensification appears to be due to two factors related to upper-level core venting: 1) the MSLP is affected through a hydrostatic adjustment to reduced inner eyewall energy values and 2) the upper part of the eyewall stabilizes due to outward energy flux. However, due to the 3km resolution of the model, it was difficult to determine the role venting-related turbulence played in the end of Jangmi's intensification.

6. Conclusion

Research over the past 4 decades has established that environmental forces at large radii have a significant impact on tropical cyclone intensification. It has also been established that environmental vertical wind shear has a detrimental effect on TC strength. This has been confirmed repeatedly even in the last 5 years (Paterson et al., 2005; Zeng et al., 2007, 2008; Garner et al., 2009; Hendricks et al., 2009). While small amounts of vertical shear have been seen as beneficial to TC development (Tuleya & Kurihara, 1981; Paterson et al., 2005), shears above 8-12m/s (DeMaria Kaplan, 1999; Wong and Chan, 2004; Paterson et al., 2005) have proven deleterious to TC intensity and structure. The question is how this works.

Generally accepted is the fact that, overall, the TC approximates a Carnot heat engine. These storms convert heat into work. Any interaction that inhibits this (e.g., internal dynamics, large-scale environmental flow, or ocean welling) will keep a TC from reaching its maximum potential intensity. Theories as to how vertical shear keeps a TC from its MPI are

myriad, yet they generally are seen as either relating to the dynamics or thermodynamics. The theories based on a fluxing of low-entropy air into the core of a TC have found support (Frank and Ritchie, 2001; Tang and Emanuel, 2010), as have the theories stating that down drafts of low entropy-air into the near-core boundary layer lessen eyewall buoyancy and thus TC intensity (Riemer et al., 2009; Tang & Emanuel, 2010). Works on the dynamical aspect have mostly concentrated on the ways by which TCs are able to cope with high levels of vertical shear (Jones, 1995; Schechter et al. 2002; Reasor, et al., 2004) rather than how the TC's intensification is detrimentally affected; it thus appears that a TC's intensification is ultimately inhibited through mostly thermodynamic processes.

Nevertheless, despite decades of effort, the true nature of relationship between vertical wind shear and TC intensification is not properly understood. Along with a lack of proper model initialization, the perpetual mystery behind the TC's interaction with its environment is one of the major issues behind the community's lack of ability in forecasting TC intensity change. The frustrations voiced in solving this mystery have been myriad. For example, although he performed a much-cited modeling study, DeMaria (1996) expressed the need for detailed observations to determine the true effect of shear on TC midlevel temperature perturbations. He went on to clearly state the need for three-dimensional model simulations with explicitly resolved convection in order to discern the feedback process between the vertical temperature structure and convection near the TC center, which process is key to understanding the shear-intensity relationship. Despite the confident pronouncements that resulted from their TC composite analysis, Knaff et al. (2004) made the concession that their symmetric analysis could not determine how the warm-core erosion occurs, partially due to the coarse (50km) resolution of the AMSU. Even Rotunno et al. (2009) expressed the need for still higher resolution and computing resources, yet lamented the computational cost of the then-current experiments.

One of the ways forward appears to be the proper parameterization, or explicit resolution of the turbulent eddies in the near core region of TCs, especially as they relate to the transport of entropy into and out of the TC eye (Frank and Ritchie, 2001; Bryan and Rotunno, 2009; Rotunno et al., 2009). The impact of this turbulence is large, as, when parameterized, it looks to consistently affect both the radius of the eyewall and the TC's maximum tangential velocity (Rotunno et al., 2009). It appears that a significant amount of these eddies are occurring on the order of 100m (Rotunno et al., 2009), however, the computational cost of routinely simulating a TC at that resolution is currently too expensive. Thus, large-eddy simulations (LES) will be primarily used to determine the eddy-diffusion coefficients necessary to properly parameterize these motions when using a grid spacing on the order of a kilometer.

Going forward, increasing wind observations and the assimilation of these wind measurements into the models would improve model initial conditions in terms of the accurate representation of the wind shears and thus enhance the numerical model's ability to produce accurate TC intensity forecasts (e.g., Pu et al. 2008). The future in the shear-intensity area of research looks particularly dependent on increases in computing power, which will enable scientists to examine the above questions without as much of a reliance on parameterizations. It appears that many of the above issues ultimately won't be resolved until simulations are able to explicitly resolve the small scale convection and turbulent eddies which populate (and affect) much of the TC inner vortex, while also properly simulating environmental effects at 500km radius from the TC center.

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This book represents recent research on tropical cyclones and their impact, and a wide range of topics are covered. An updated global climatology is presented, including the global occurrence of tropical cyclones and the terrestrial factors that may contribute to the variability and long-term trends in their occurrence. Research also examines long term trends in tropical cyclone occurrences and intensity as related to solar activity, while other research discusses the impact climate change may have on these storms. The dynamics and structure of tropical cyclones are studied, with traditional diagnostics employed to examine these as well as more modern approaches in examining their thermodynamics. The book aptly demonstrates how new research into short-range forecasting of tropical cyclone tracks and intensities using satellite information has led to significant improvements. In looking at societal and ecological risks, and damage assessment, authors investigate the use of technology for anticipating, and later evaluating, the amount of damage that is done to human society, watersheds, and forests by land-falling storms. The economic and ecological vulnerability of coastal regions are also studied and are supported by case studies which examine the potential hazards related to the evacuation of populated areas, including medical facilities. These studies provide decision makers with a potential basis for developing improved evacuation techniques.

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